Draft version February 1, 2008
Preprint typeset using LaTeX style emulateapj v. 19/02/01

ON THE RELATIONSHIP BETWEEN STELLAR ROTATION AND RADIUS IN YOUNG CLUSTERS

L. M. Rebull[1], S. C. Wolff[2], S. E. Strom[2], R. B. Makidon[3]

Draft version February 1, 2008

ABSTRACT

We examine the early angular momentum history of stars in young clusters via 197 photometric periods in the Orion Flanking Fields, 83 photometric periods in NGC 2264, and 256 measurements of $v \sin i$ in the ONC. We show that PMS stars, even those without observable disks, apparently do not conserve stellar angular momentum as they evolve down their convective tracks, but instead evolve at nearly constant angular velocity. This result is inconsistent with expectations that convective stars lacking disks should spin up as they contract, but paradoxically consistent with disk-locking models. We briefly explore possible resolutions, including disk locking, birthline effects, stellar winds, and planetary companions. We have found no plausible explanations for this paradox.

Subject headings: stars: pre-main sequence — stars: rotation

1. INTRODUCTION

Observations over the past decade have established that most–and probably all–pre-main sequence (PMS) stars are surrounded by disks during early stages of their evolution, and that a substantial portion of their final mass is accreted from these disks. However, the prediction that this accretion will cause the stars to rotate at close to their breakup speed (*e.g.* Durisen et al. 1989) is not borne out by observations. Most PMS stars have rotational velocities (v) of no more than a few tens of km s^{-1}. By contrast, the typical breakup velocity at $\sim$1 Myr is $\sim$300 km s^{-1}.

Explanations of the observed slow rotation have invoked a magnetic field that is rooted in the central star and intercepts the disk (Königl 1991). The net consequence of this interaction is a braking torque transmitted to the star by field lines penetrating the disk beyond the co-rotation radius (where the angular velocity ω of the disk matches that of the star). This braking torque exactly balances the spin-up torque exerted by the material inside the co-rotation radius. This model predicts that stars will be locked to their disks and will rotate slowly until the time that the disk is dissipated. Other models (*e.g.* Shu et al. 2000) make use of a wind, launched from the stellar magnetosphere-disk boundary to carry away stellar angular momentum (J), thus reducing rotation rates to well below breakup. By contrast, stars without disks should conserve J and spin up as they contract and evolve down their Hayashi tracks.

Considerable observational effort has been devoted to finding empirical correlations between rotation rates and the presence or absence of observable disks; although such correlations appeared in early studies (*e.g.* Edwards et al. 1993, Choi & Herbst 1996), recent results are ambiguous at best (*e.g.* Rebull 2001; Stassun et al. 1999). Over the past few years, rotation periods P or projected rotational velocities $v \sin i$ have been measured for large samples of PMS stars $\sim$0.1-2.5 M$_\odot$ and of age $\lesssim$3 Myr. These data sets are now large enough to provide direct evidence of how J changes as stars of different masses evolve down their convective tracks. In this paper, we examine the early J history of stars surrounded by disks and those that lack disks. We show that PMS stars, *even those without observable disks*, do not conserve angular momentum as they evolve toward the ZAMS but instead evolve at nearly constant angular velocity. This result is inconsistent with expectations that convective stars lacking disks should spin up as they contract, but paradoxically consistent with disk-locking models.

2. THE OBSERVATIONS

The data sets that we draw on for this paper are 256 measurements of $v \sin i$ in the Orion Nebula Cluster (ONC) by Rhode et al. (2001; RHM); 197 photometric periods (P) for the Flanking Fields (FF) that surround the ONC (Rebull 2001, Rebull et al. 2000); and 83 stars with P in NGC 2264 (Makidon et al. 2001, Rebull et al. 2001). The age distribution for Orion peaks near $\sim$1 Myr, while NGC 2264 peaks near $\sim$1 Myr but contains significant numbers of stars out to $\sim$3-4 Myr. Together, these clusters allow us to examine changes in stellar angular momenta over a total range in stellar radius of $\sim$0.4 dex. In order to estimate accurate stellar radii and to determine the presence or absence of a disk, we required that spectral types along with $I-K$ and $V-I$ photometry be available for all the stars included in the present study. While other disk indicators (*e.g.* UV excess, Hα emission) are available for subsets of the Orion and NGC 2264 databases, only $I-K$ is widely available. All stars with an $I-K$ color redder by 0.3 mag than expected based on spectral type were considered to be surrounded by disks (cf. Rebull 2001 and references therein). We note that 26/197 (13%) stars in the Orion FF sample and 20/83 (24%) in the NGC 2264 sample have $I-K$ excesses, whereas 60% of the stars in the ONC sample have such an excess.

Stellar temperatures ($T_{\rm eff}$) were assigned according to

[1] National Research Council Resident Research Associate, NASA/Jet Propulsion Laboratory, M/S 169-506, 4800 Oak Grove Drive, Pasadena, CA 91109 (luisa.rebull@jpl.nasa.gov)
[2] NOAO, 950 N. Cherry Ave, Tucson, AZ 87526
[3] STScI, 3700 San Martin Dr, Baltimore, MD 21218

spectral types and luminosities (L) were derived from I_C magnitudes with reddening estimated from colors and spectral types following Hillenbrand (1997). We adopted distance moduli of 8.36 for Orion (Genzel et al. 1981) and 9.40 for NGC 2264 (Sung et al. 1997). Radii (R) were calculated using the assigned values of L and $T_{\rm eff}$. Photometric uncertainty, the amplitude of the periodic modulation, uncertainties in the reddening correction, and errors in classification all contribute to errors in L and $T_{\rm eff}$ and hence to uncertainty in R. The distribution of empirically-determined errors in $\log R$ is strongly peaked near ± 0.1. The errors in P are less than 1%.

The $v \sin i$ data for the ONC have sufficient resolution to measure only velocities greater than $\sim$11 km s^{-1}, corresponding to $P \lesssim$ 6d for a typical PMS star in our sample. The P measurements are sensitive to a much broader range of periods, viz $P \sim 0.3 - 25$d ($v \sim 3 - 300$ km s^{-1}), encompassing much slower rotation velocities than do the published $v \sin i$ measurements. Approximately half of the stars with $v \sin i$ measurements by RHM were chosen because they had known P. The other half were selected as a control sample of objects without known P from the same portion of the HR diagram. RHM show there is no statistically significant difference between the $v \sin i$ distributions of the periodic and control samples, leading to the important conclusion that samples of stars found to show photometric periods can be taken as a fair representation of the range of rotational characteristics of PMS stars.

3. ANALYSIS

If stars conserve angular momentum (J) as they evolve down their convective tracks, then we would expect that $J = MvR$ would remain constant, but only if J is conserved in the outermost observable layer of the star. We expect fully convective stars to rotate as solid bodies. Examination of theoretical models of PMS stars (*e.g.* Swenson et al. 1994) indicates that the predicted changes in surface rotation rate as the star evolves down the convective track are indistinguishable for the two extreme cases of solid body rotation and local conservation of J (*i.e.* J conservation in spherical shells). Along the convective track contraction is nearly homologous, and changes in I directly track changes in R^2. If J is conserved, then vR is constant and $P = 2\pi R/v$ should be $\propto R^2$. On the other hand, if angular velocity $\omega = v/R$ is constant, as predicted for disk-locking, then P is constant.

In Figure 1, we plot P and $j = \frac{2Rv}{5}$ vs. R, where j is computed as in Rebull (2001)[4]. It is immediately apparent that there is no variation of P with R, but that j changes with R, consistent with conservation of ω. The errors in log R would have to be about 0.5 dex (5 times larger than we estimate them to be) in order to mask the decline in P expected for the case of conservation of J. We see no substantial difference between these two clusters, except for the fact that the stars in NGC 2264 include older objects with smaller radii. We find no significant difference in the period-radius relationship of stars with and without $I - K$ excesses, though there may be some marginal tendency for diskless stars to have the shortest periods. We have divided our sample into two bins: $P <$3 d and $P >$3 d. The disk fractions are for Orion 0.1$\pm$0.03 and 0.2$\pm$0.1 respectively, and for NGC 2264, both fractions are 0.3$\pm$0.1.

To enable more direct comparison with the RHM results for the inner ONC, we have converted the Orion FF and NGC 2264 periods to v. The P data provide an estimate of v rather than $v \sin i$ and are systematically higher for this reason. For our purposes, it only matters that the data within each group are internally consistent. We have subdivided the $v \sin i$ and v measurements following RHM according to $T_{\rm eff}$ and L, corresponding to a subdivsion by mass (M) for stars on convective tracks, and with age for stars of a given M. For each bin we show in Table 1 the average v or $v \sin i$. To first order, each column of the Table can be viewed as following the evolution of stars of a given mass down a convective track.

As can be seen from Table 1, the average value of v or $v \sin i$ *decreases* with L at fixed M, rather than increasing as one would expect for conservation of stellar J. In constructing these averages for the ONC sample, we have assigned 11 km s^{-1} as the $v \sin i$ for all of those stars for which only upper limits are available. A detailed examination of the data in RHM shows that the percentage of stars rotating at or below this upper limit increases with decreasing L, and so the decline in $v \sin i$ with decreasing L is probably even stronger.

Table 2 tabulates the quantities v/R, which is proportional to ω, and vR, which is proportional to J. v/R is constant within each mass group, within about a factor of $\sim$2, regardless of how far the stars have evolved down their convective tracks. In other words, it appears as if some agent is keeping stars close to constant ω over nominal ages from 0.1-3 Myr. We note that this result stands whether stars appear to have $I - K$ excesses or not.

4. DISCUSSION

Prior to this survey, we expected that PMS stars lacking observable disks should spin up as they contract along convective tracks. The observations show that they do not, despite the fact that these stars span a range of 0.4 dex in log R, which should correspond to a decrease in log P of 0.8 dex. We briefly explore several possible explanations.

4.1. *Disk-Locking with Gaseous Disks*

The absence of evolution in the distribution of periods among PMS stars as they contract is consistent with what would be expected for disk-locking. Absent observable evidence of disks from infrared excess emission arising from micron-size dust grains, we would need to posit linkage between stellar magnetospheres and disks in which small solid particles have been agglomerated into larger bodies, leaving behind only gas. Detection of such disks via H_2 or CO emission awaits more sensitive measurements than possible at present. A search for dust-free gaseous disks with SIRTF appears to be the most promising near-term approach.

4.2. *Radius Changes Reflect Initial Conditions (Birthline Effects) Rather Than Evolution*

[4] Computed assuming spherical stars rotating as solid bodies, $j = \frac{J}{M} = \frac{I\omega}{M} = \frac{2Rv}{5} = \frac{4\pi R^2}{5P}$, where I=moment of inertia, and all other terms have been defined.

Suppose that (1) stars in Orion and NGC 2264 were born in a single burst of star formation ∼1 Myr ago; (2) the range in L (equivalently R) for the PMS stars in these clusters does not reflect evolution down convective tracks, but rather differences in mass accretion rate ($\dot{M}$) that force stars to evolve along different 'birthlines' and therefore to arrive at different initial luminosities along the convective tracks (Palla & Stahler 1992); and (3) PMS stars are locked to a particular P so long as they are surrounded by accretion disks. In this picture, the observed distribution of stars along a convective track for a given mass then reflects a range of $\dot{M}$: protostars with higher $\dot{M}$ have larger initial radii and lie higher in the color-magnitude diagram following the end of the accretion phase (see also Hartmann et al. 1997). The similarity of P at different R then follows from the assumption that stars are locked to their disks for much (nearly all) of their ∼1 Myr accretion phase.

The difficulty with this picture lies with the additional requirement that stellar L cannot have decreased much since the stars were deposited on their convective tracks. If stars that formed through high $\dot{M}$ and were initially deposited high on their convective tracks had subsequently evolved downwards, we would expect to see a 'tail' of stars that have spun up to shorter P mixed in with the ensemble of objects that started their evolution at smaller R. We do not. The only way to resolve this contradiction and still maintain conservation of stellar J would be to identify a mechanism for halting or slowing evolution toward smaller radii for a time comparable to ∼1 Myr. The problem is even more severe when considering those stars in NGC 2264 with apparent ages ∼3 Myr, thus requiring L evolution for stars with high $\dot{M}$ to be delayed for an even longer time.

4.3. *Angular Momentum Loss via Stellar Winds*

Stellar winds loaded onto open magnetic field lines can exert a spindown torque on stars. However, this mechanism has been shown to be ineffective for PMS stars because, during this phase of evolution, the timescale for spindown exceeds the evolutionary timescale by a few orders of magnitude (*e.g.* MacGregor and Charbonneau 1994) – fully convective stars are assumed to rotate as solid bodies, and the wind must slow down the entire star. Furthermore, this conclusion is nearly independent of the rate of mass loss. Calculations (*e.g.* Kawaler 1988) show that the rate of change of J depends on the product of the mass loss rate and the square of the Alfven radius, but the Alfven radius varies inversely as some power of the mass loss rate, with the specific power depending on the configuration of the magnetic field. For a field geometry "intermediate" between a dipolar and a radial field, dJ/dt does not depend on mass loss rate at all (Bouvier et al. 1997). The only circumstance under which magnetic winds could play an important role in slowing the rotation of PMS stars would be if there were some way in which to decouple the outer layers of the star from the interior, *i.e.* if J were conserved locally, and the wind had to slow down only a thin outer layer of the star. Such decoupling is not expected for fully convective stars.

Moreover, any putative wind-driven J loss mechanism would have to cease on timescales of no more than a few Myr in order to account for the significant population of rapidly rotating main sequence stars in young clusters such as Alpha Persei (*e.g.* Stauffer et al. 1989); such stars require spinup from the PMS to the ZAMS.

4.4. *Angular Momentum Loss via Tidally-Locked Planetary Companions*

Recent theoretical models indicate that tidal locking between a close-in Jupiter-mass planet and the parent star can transfer spin J from the star to the orbital J of the planet, thus slowing the rotation of the star while driving the planet into a larger orbit.

Unfortunately, this effect is not large enough to account for the observations reported here. The difficulty lies in the apparent incompatibility of two requirements: (1) the putative planet must be located close enough to the star to produce significant tidal distortion; and (2) the planet must be located far enough from the star to dominate the J of the system (and thus be able to create significant changes in stellar J with only modest orbital evolution). A simple calculation (cf. Trilling et al. 1998) in which we assume a Jupiter-mass planet orbiting a PMS star at a distance of 0.1 AU suggests that J regulation by tidal locking to such a planet fails by 2 orders of magnitude.

5. SUMMARY

Previous attempts to test the disk-locking hypothesis have attempted to establish a correlation between rotation rates and the presence or absence of a disk. We see only weak evidence for this correlation, which has also been questioned by many previous authors (*e.g.* Rebull 2001, Stassun et al. 1999). It is possible that intrinsic variations in rotation rates at the time that stars are deposited on their birthlines is sufficient to mask such a simple correlation. What we do see is that the trends in $< v \sin i >$ and in the P of PMS stars in Orion and in NGC 2264 are consistent with evolution down convective tracks at constant angular velocity (ω), within a factor of ∼2. The data are not at all consistent with conservation of stellar angular momentum (J). It appears highly unlikely that the errors in the observations could be large enough to mask conservation of stellar J. The errors in $v \sin i$ and P are small, and the conclusion that stars do not spin up as they age depends only on the assumption that the stars are properly ordered according to $T_{\rm eff}$ and L; highly accurate calibrations of $T_{\rm eff}$ and L are not required. Conservation of ω is consistent with the hypothesis that J is controlled by disk-locking. However, ω appears to be conserved, or nearly so, for both those stars with disks and those for which disks are, at least so far, undetectable by observation. We have found no plausible explanation for this paradox.

We find no evidence for spin-up of stars over the age range spanned by the current observations, which is ∼3 Myr. Such spin-up must ultimately occur in order to account for the rapid rotators seen on the main sequence in young clusters such as Alpha Persei (Stauffer et al. 1989). However, recent observations of $v \sin i$ for a small sample of stars in the 10 Myr old TW Hya association (Torres et al. 2000; Sterzik et al. 1999) suggest mean $v \sin i$ values similar to those found among the oldest stars in our NGC 2264 sample, despite the fact that the nominal radii among the TW Hya stars are smaller by 50%. These ob-

servations suggest the urgent need for a campaign focused on mapping the angular momentum evolution of low mass stars in the age range 3−30 Myr so as to understand when rotational spinup in response to contraction takes place.

We wish to thank Jonathan Lunine and Lee Hartmann for several helpful discussions regarding possible explanations for the apparent paradox explored here. SES acknowledges support from the NASA Origins of Solar Systems program which enabled analysis of the NGC 2264 data. We thank Mark Adams for multiple comments and support during the early phases of the investigation of periodic stars and the McDonald Observatory for the award of guest investigator time on the 0.9m telescope.

REFERENCES

Bouvier, J., Forestini, M., & Allain, S. 1997, A&A, 326, 1023
Choi, P., & Herbst, W. 1996, AJ, 111, 283
Durisen, R. H., Yang, S., Cassen, P., & Stahler, S. 1989, ApJ, 345, 959
Edwards, S., Strom, S. E., Hartigan, P., Strom, K. M., Hillenbrand, L. A., Herbst, W., Attridge, J., Meriill, K. M., Probst, R., & Gatley, I., 1993, AJ, 106, 372
Genzel, R., Reid, J. J., Moran, J. M., & Downes, D. 1981, ApJ, 244, 884
Hartmann, L., Cassen, P., & Kenyon, S. J. 1997, ApJ, 475, 770
Hillenbrand, L. A. 1997, AJ, 113, 1733
Königl, A. 1991, ApJ, 370, 39
Kawaler, S. D. 1988, ApJ, 333, 236
MacGregor, K. B., & Charbonneau, P. 1994, in ASP Conf. Ser. 64, Cool Stars, Stellar Systems, and the Sun, Eighth Cambridge Workshop, ed. J.-P. Caillaut (San Francisco:ASP), 174
Makidon, R., Rebull, L., Strom, S., Adams, M., & Patten, B. 2001, in preparation
Palla, F., & Stahler, S. W. 1992, ApJ, 392, 667
Rebull, L. M. 2001, AJ, 121, 1676
Rebull, L. M., Hillenbrand, L., Strom S. E., Duncan, D. K., Patten, B. M., Pavlovsky, C. M., Makidon, R., & Adams, M. T. 2000, AJ, 119, 3026
Rebull, L. M., Makidon, R. B., Strom, S. E., Hillenbrand, L. A., Birmingham, A., Yagi, H., Jones, B. F., Adams, M. T., & Patten, B. M. 2001, in preparation
Rhode, K. L., Herbst, W., & Mathieu, R. D. 2001, AJ, in press (RHM)
Shu, F., Najita, J., Shang, H., & Li, Z.-Y. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss & S. S. Russell (Tucson: University of Arizona Press), 789
Stassun, K. G., Mathieu, R. D., Mazeh, T., & Vrba, F. J. 1999, AJ, 117, 2941
Stauffer, J. R., Hartmann, L. W., & Jones, B. F. 1989, ApJ, 346, 160
Sterzik, M., Alcalá, J., Covino, E., Petr, M. 1999, A&A, 346, L41
Sung, H., Bessell, M. S., & Lee, S-W. 1997, AJ, 114, 2644
Swenson, F. J., Faulkner, J., Rogers, F. J., & Iglesias, C. A. 1994, ApJ, 425, 286
Torres, C., da Silva, L., Quast, G., de la Reza, R., Jilinski, E. 2000, AJ, 120, 1410
Trilling, D. E., Benz, W., Guillot, T., Lunine, J. I., Hubbard, W. B., & Burrows, A. 1998, ApJ, 500, 428

Table 1
Distribution of v or $v \sin i$.

cluster	$\log T_{\rm eff} \rightarrow$ bin[a] $\log L/L_{\odot}\downarrow$ bin[a]	A (3.730-3.682) $<v>$[b]	 num[c]	B (3.682-3.634) $<v>$	 num	C (3.634-3.586) $<v>$	 num	D (3.586-3.538) $<v>$	 num	E (3.538-3.490) $<v>$	 num
ONC	1 (1.48 - 1.11)	33±13	3	41±10	5						
	2 (1.11 - 0.74)	30±4	6	26±6	4	14	1				
	3 (0.74 - 0.37)	26±5	7	15±4	4	34±12	7	35±9	5		
	4 (0.37 - 0.00)	19±7	2	17±3	13	17±3	18	23±4	17	34±15	3
	5 (0.00 - −0.37)	12	1			20±8	6	19±3	41	19±2	22
	6 (−0.37 - −0.74)					18±7	3	16±4	18	2-±3	44
Orion FF	1										
	2	380	1			266	1				
	3	34±7	3	65±22	3	52±17	7	20±12	2	67	1
	4	62±42	4	41±10	12	24±4	17	58±13	7		
	5			12	1	24±6	18	37±8	20	48±14	17
	6					13±7	2	32±7	22	34±6	35
NGC 2264	1										
	2					85	1				
	3	35	1	59±33	2	55	1				
	4	21±8	6	28±12	5	36±20	3	30±7	2		
	5	28	1	23±11	5	23±8	11	40±13	11	36	1
	6	4	1	15	1	48	1	23±6	18	101±39	4

[a]Defined exactly as in RHM; subdivisions according to $T_{\rm eff}$ and L correspond to subdivsions by M for stars on convective tracks, and with age for stars of a given M.

[b]$< v \sin i >$ for ONC, $< v >$ for Orion FF and NGC 2264.

[c]Number of stars in the bin.

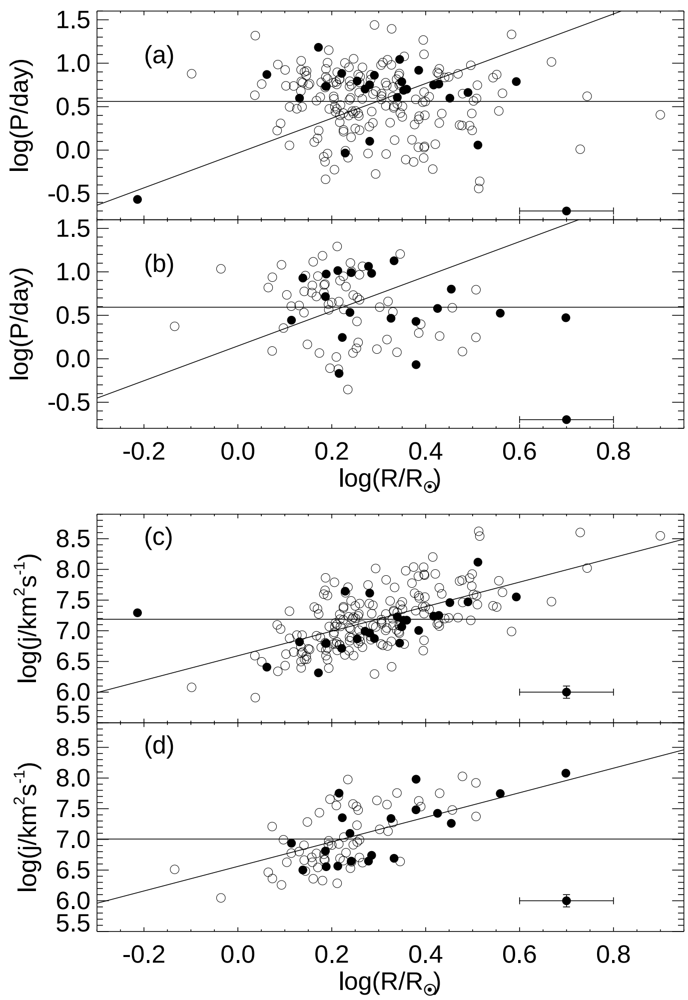

FIG. 1.— Period vs. R (a-b) and angular momentum ($j = \frac{2Rv}{5}$) vs. R (c-d) for stars in the Orion Flanking Fields (a,c) and NGC 2264 (b,d), without $I - K$ excesses (open symbols) and with excesses (filled symbols). Typical error bars are indicated. In a & b, lines correspond to a slope of 0 (constant P or ω and j changes), and a slope of 2 (P changes and j conserved); in c & d, lines also have slopes of 0 and 2, but slope of 0 corresponds to constant j and slope of 2 corresponds to constant P.

Table 2
Trends in angular momentum ($\propto vR$) and angular velocity ($\propto v/R$).

cluster	$\log T_{\rm eff} \rightarrow$ bin[a] $\log L/L_{\odot}\downarrow$ bin[a]	A (3.730-3.682) v/R[b]	vR[b]	B (3.682-3.634) v/R	vR	C (3.634-3.586) v/R	vR	D (3.586-3.538) v/R	vR	E (3.538-3.490) v/R	vR
ONC	1 (1.48 - 1.11)	6	191	6	296						
	2 (1.11 - 0.74)	8	112	6	123	2	82				
	3 (0.74 - 0.37)	11	64	5	46	9	131	7	168		
	4 (0.37 - 0.00)	12	31	8	34	7	43	7	72	9	133
	5 (0.00 - -0.37)	11	13			12	33	9	39	7	48
	6 (-0.37 - -0.74)					17	19	12	21	12	33
ONC FF	1										
	2	116	1246			50	1428				
	3	16	75	22	197	16	177	5	81	12	375
	4	32	120	19	90	10	63	21	165		
	5			12	14	14	44	19	77	21	116
	6					11	16	21	49	21	57
NGC 2264	1										
	2					17	428				
	3	13	95	19	191	15	199				
	4	13	38	12	65	15	90	11	87		
	5	23	35	16	35	15	38	20	83	17	78
	6	5	4	22	12	35	69	15	38	60	173

[a]Defined exactly as in RHM; subdivisions according to $T_{\rm eff}$ and L correspond to subdivsions by M for stars on convective tracks, and with age for stars of a given M.

[b]$< v \sin i >$ for ONC, $< v >$ for Orion FF and NGC 2264. vR would be constant if stellar J is conserved, and v/R would be constant if ω conserved. Note that vR changes, whereas v/R is constant to within a factor of $\sim$2.